Defense **Horizons**

Number 18

A publication of the
Center for Technology and National Security Policy
National Defense University

OCTOBER 2002

High-Energy Lasers: Technical, Operational, and Policy Issues

by Elihu Zimet

Overview

After more than 30 years of technology development and many billions of dollars in investment, the Department of Defense is poised to operationally deploy its first high-energy laser (HEL) weapon system, the airborne laser. The unique attributes of an HEL—speed-of-light delivery of energy, surgical precision, variable lethality, and multiple target engagement—could significantly alter the balance between offensive and defensive weapons or provide options for nonlethal weapons. On the other hand, the long development period and large outlay of funding to date suggest the significant technical, operational, and policy challenges of fielding such systems.

This paper considers the unique and promising attributes of HEL weapon systems and examines the technical challenges, at both the system and component level, that need to be overcome for an HEL to be competitive against alternative weapon systems. Related operational and policy issues are also discussed. The paper concludes that advances in HEL technology emphasizing speed, precision, and flexibility together with the ongoing transformation of the military services have both indicated the need and provided the opportunity for further HEL development and testing.

Laser Technologies under Development

Three different types of high-energy laser (HEL) are currently under development: the chemical laser, the solid-state laser, and the free-electron laser (FEL), each of which uses a different principle to produce a laser beam. The most developed concept, and the only one yet to be scaled to HEL power levels, is the chemical laser, in which energy release comes from a chemical reaction. This is the laser type employed in the airborne laser (ABL) and in the U.S. Army/Israeli Tactical High-Energy Laser (THEL). It is also the technology employed in other HEL demonstrator systems such as the Space-Based Laser (SBL) and the Mid-Infrared Advanced Chemical Laser (MIRACL) high-energy laser at White Sands, New Mexico. The second type of laser, the electrically powered solid-state laser, could provide benefits in propagation, lethality, and engineering design (less complex, smaller size, less sensitive to shock). The third system, the free-electron laser, also electrically powered, is the most complex, but is the only laser concept that is completely wavelength-selectable. For selected applications, such as transmission through the atmosphere at sea level, this attribute is critical. While there is no set power level threshold that defines a high-energy laser, average powers of tens of kilowatts to megawatts are generally considered to define high power in a weapons sense.

The HEL has the potential to address a range of applications and missions from ground to space. Ground-based lasers have been considered mostly for tactical air defense, which is the role of the THEL, and also for antisatellite (ASAT) capability. Recently, lasers

Center for Technology and National Security Policy

The National Defense University (NDU) established the Center for Technology and National Security Policy in June 2001 to study the implications of technological innovation for U.S. national security policy and military planning. The center combines scientific and technical assessments with analyses of current strategic and defense policy issues. Its major initial areas of focus include: (1) technologies and concepts that encourage and/or enable the transformation of the Armed Forces, (2) developments by defense laboratories, (3) investments in research, development, and acquisition and improvements to their processes, (4) relationships among the Department of Defense, the industrial sector, and academe, and (5) social science techniques that enhance the detection and prevention of conflict. The staff is led by two senior analysts who hold the Roosevelt Chair of National Security Policy and the Edison Chair of Science and Technology and who can call on the expertise of the NDU community and colleagues at institutions nationwide. The papers published in the *Defense Horizons* series present key research and analysis conducted by the center and its associate members.

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **OCT 2002**	2. REPORT TYPE **N/A**	3. DATES COVERED **-**
4. TITLE AND SUBTITLE **High-Energy Lasers: Technical, Operational, and Policy Issues**		5a. CONTRACT NUMBER
		5b. GRANT NUMBER
		5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)		5d. PROJECT NUMBER
		5e. TASK NUMBER
		5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **National Defense University Center for Technology and National Security Policy Fort McNair Washington, DC 20319**		8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)		10. SPONSOR/MONITOR'S ACRONYM(S)
		11. SPONSOR/MONITOR'S REPORT NUMBER(S)
12. DISTRIBUTION/AVAILABILITY STATEMENT **Approved for public release, distribution unlimited**		
13. SUPPLEMENTARY NOTES **The original document contains color images.**		
14. ABSTRACT		
15. SUBJECT TERMS		

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**UU**	**8**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

have been proposed for mobile ground-based systems to use against air and ground targets. The Navy developed the MIRACL chemical laser system for ship defense against cruise missiles in the early 1980s; however, it requires a different laser at a shorter wavelength to solve propagation problems associated with self-defense in the maritime environment. The current leading Department of Defense (DOD) program is the ABL system for boost-phase ballistic missile defense. Another airborne concept, this one addressing ground targets, is the Airborne Tactical Laser (ATL). Finally, the Space-Based Laser is focused on high-altitude boost phase and mid-phase ballistic missile defense. All of these options illustrate the potential military value of laser weapons, but technological, operational, and policy challenges remain.

History

Enthusiasm for high-energy lasers and other directed energy concepts such as particle beams and high-power microwaves has waxed and waned during its 30 years of technology development. In the early 1970s, the services were highly interested in HELs as an alternative to conventional guns and missiles. The Navy mission of interest was, and still is, shipboard defense against maneuvering low-altitude cruise missiles that could saturate the Phalanx gun system. The Air Force in this period, using a multikilowatt carbon dioxide (CO^2) laser, built an airborne demonstrator called the Airborne Laser Laboratory to experiment with air superiority and missile defense. The Army also developed a multikilowatt CO^2 laser for a tracked vehicle called the Mobile Test Unit to demonstrate effectiveness against light vehicles and sensors. None of these early systems showed the potential to compete successfully against missile and gun evolution because their capability did not match initial hopes and expectations. Since these initial demonstrator programs, the Navy has developed a layered missile system employing the rolling airframe missile, the enhanced Sea Sparrow missile, and the Standard Missile coupled with enhanced surveillance and targeting as well as electronic support measures. The Air Force has developed the highly capable advanced medium-range air-to-air missile for air superiority, while the Army has made significant progress in penetrating-round technology for antiarmor.

recent advances in FEL technology have rekindled Navy interest, while advances in solid-state laser technology have prompted the Air Force and Army to look again

In the early 1980s, the Reagan administration vision of a shield against ballistic missile attack led to the formation of the Strategic Defense Initiative Office (SDIO) and a new interest in and requirement for HEL. Service funding transferred to SDIO initiated a very ambitious program in chemical and free-electron lasers. SDIO continued to support the MIRACL chemical laser at White Sands until the late 1980s, when a series of tests against a head-on, low-altitude target produced discouraging results, and Navy involvement in HEL waned. While Army interest in tactical-vehicle-mounted lasers also waned in the 1980s, the service assumed management of the SDIO ground-based FEL program. The goal of this system was to defeat strategic ballistic missiles in the boost phase by redirecting a powerful beam from the ground with a low orbit mirror system. The program objectives were well beyond the technology level of the FEL, which was the laser system chosen because of its potential for optimized propagation at shorter wavelengths than the chemical laser. Eventually, the program was terminated.

Recent advances in FEL technology have rekindled Navy interest, while advances in solid-state laser technology have prompted the Air Force and Army to look again at tactical applications. The Army is the lead service for the Advanced Concept Technology Demonstration (ACTD) THEL program. During the past 2 years, the Marine Corps has looked at the concept of employing an HEL (a scaled-down version of the ABL chemical oxygen iodide laser [COIL]) in a helicopter or V–22 as a gunship in an urban environment. This ACTD, which is managed by the Air Force, is called the Airborne Tactical Laser (ATL). Although the Navy and Army have renewed interest and the Marine Corps has become active in HEL development, the Air Force has been the principal developer of HEL technology since the 1980s. The ABL, begun in 1994, utilizes a COIL and an adaptive optic beam control system to address the ballistic missile threat in the boost phase from an airborne platform. The Air Force continues to invest in technology to enhance this concept and has even looked at the requirements for a fighter laser weapon system.

Three years ago, individuals in Congress and the Office of the Secretary of Defense became concerned that the investment in high-energy lasers was almost entirely in development of three chemical laser systems (ABL, SBL, and THEL), with only a limited budget addressing next-generation laser concepts and supporting technology areas such as optics. The result was the Floyd D. Spence National Defense Authorization Act for fiscal year 2000, which directed DOD to prepare a "detailed plan to develop and mature high-energy laser technologies." DOD has subsequently developed such a plan and created the DOD High-Energy Laser Joint Technology Office that has its own funding line for science and technology. The formation of this office and the potential to leverage its funding have stimulated new investment by the services.

Defense planners are taking a fresh look at HEL weapon systems. Longstanding missions such as ship self-defense are under investigation to determine if advances in both HEL technology and electric on-board power, compared to advances in the threat capability coupled with new threat scenarios, have changed the calculus of ship defense to favor HEL weapons. In addition, new requirements such as urban warfare, the small boat threat, and the projected utility of nonlethal weapons, in addition to the heightened interest in missile defense, have spurred renewed interest in HEL.

Elihu Zimet is a senior research fellow in the Center for Technology and National Security Policy at the National Defense University. Dr. Zimet may be contacted at zimete@ndu.edu or by phone at (202) 685–3586.

Attributes

To reach deployment, a new weapon system must either show significant capability or cost advantages over existing systems or address a priority requirement that cannot be met by incremental improvements to an existing system. This section considers key HEL attributes, the principal attribute being the speed-of-light delivery of energy. The HEL could be a weapon of choice for a transformational military concerned with homeland defense, asymmetric threats from rogue powers and terrorists, and urban warfare, as well as the more traditional military missions on the battlefield and at sea.

Speed-of-light reaction time. A look at typical times available for the engagement of a target compared with the flight time of projectiles and missiles highlights the continued interest in HEL weapons. In a ballistic missile defense scenario, tactical considerations for an airborne defensive system lead to standoff distances of about 200 miles. A ballistic missile is most vulnerable to tracking and killing during the boost phase. For a Scud missile, the boost phase is approximately 60 seconds. If a missile is destroyed early in the boost phase, it will fall back on the area of the launch, a critical concern for nuclear, biological, and chemical warheads. If a defensive projectile or missile is fired from an aircraft at an average speed of Mach 5 (5 times the speed of sound), it will take more than 3 minutes to travel the 200 miles. This is too long a flight time for an assured kill in a boost phase engagement of a Scud missile in which the times for detection, tracking, weapons coordination, and fire control are added. By comparison, a laser beam would travel the same 200 miles in less than a millisecond. Although missiles have a finite fly-out time, their time to kill is near instantaneous and the kill is catastrophic. Lasers have essentially zero fly-out time, but they do require time, typically several seconds, to deposit enough energy into the target for a kill. The assured lethality of an HEL remains an issue that will only be resolved by convincing demonstrations.

the HEL could be a weapon of choice for a transformational military concerned with homeland defense

Another situation in which the time to destroy a threat is short is that of a ship defending itself against a supersonic cruise missile flying only a few feet above the top of the waves (so-called sea skimmers). If the threat is detected as it comes over the horizon, about 15 miles out, and is traveling at Mach 3, it will travel from detection to impact in approximately 24 seconds. If several simultaneous high-speed missiles are fired at the ship, its defensive system could be overwhelmed even if several defensive missiles are fired at the same time.

Maneuvering and crossing targets. If the same cruise missile scenario outlined above concerned a maneuvering target, the gun or missile kill would be greatly complicated, since a defensive missile typically needs a three-to-one gravity (G) advantage over the target. A maneuvering target, however, is probably even more vulnerable to an HEL. A weaving target traveling at Mach 3 and executing 20+Gs of maneuver will present minimal problems to the laser beam director in holding the beam on the target. However, a target pulling 20+Gs will be much more susceptible to breakup after being damaged by the laser. A crossing target presents its profile rather than just its nose to the HEL beam, increasing the target's vulnerability to a guidance or propellant kill. While the slewing laser beam can easily keep up with the target, the slewing greatly enhances the propagation of the beam through the air. Thus, more energy is deposited on the target, and the odds of a kill are significantly increased.

Assured lethality. The magazine for an HEL is laser-reactant fuel for a chemical laser, or electric generator fuel for both solid-state lasers and free-electron lasers. The lasers can run as long as fuel is available, which can provide for a very deep magazine. Coincidentally, the power needed to run an electric HEL and the power necessary to propel a surface combatant can be the same, particularly on the new all-electric ship concepts that generate the needed electricity. This means that fuel is available for hours of HEL run time, which in turn ensures that a target or targets can be engaged until they are destroyed (provided that enough energy is propagated through the air and deposited in the target and that the closing target does not hit the ship first). The number of simultaneous targets that can be engaged depends on the hardness of the target and the irradiance time needed for a kill, typically several seconds. In a ship defense scenario, two or three simultaneous threats might be engaged sequentially before engagement time runs out. If the threats are spaced sufficiently, only fuel or electric power limits the number of engagements.

Avoidance of collateral damage. The precision pointing and tracking of the beam director leads to the absence of collateral damage. For example, consider air defense in an urban environment. An air defense projectile or missile that does not engage a target, unless it has the ability to self-destruct, provides a real threat to people and dwellings on the ground. In contrast, an HEL does not produce unexpended rounds, and there is no additional ground threat. This attribute might make an HEL attractive for the defense of high-value buildings and facilities.

Target identification. The HEL beam director is a high-quality telescope using reflecting optics that can provide a detailed image of the target. While the reflective coatings on the mirrors are tuned to the frequency of the HEL, there is residual reflectivity at other wavelengths, including the visible. This imagery can be used to provide a positive identification of the target, which could lead to rules of engagement in operations with commercial and friendly aircraft, as well as in urban operations.

Lethal to nonlethal capability. The power output of a laser can be modulated from destruction at full power, to disable at lower power, to deny and dissuade at still lower power. This capability would be of value to the Navy in the midst of small craft of unknown intent or to an airborne laser "gunship" in an urban environment aiming at ground targets. As an alternative, a separate low-power laser could be deployed to warn away potential threats and to destroy or blind threat sensors.

Technology Challenges

Technology challenges for HEL weapon systems include the issues not only of the particular laser device employed but also of the associated optics and beam director. In addition, a systems analysis of an HEL includes an examination of weapon effectiveness, which includes the propagation of the beam to the target and the lethality of the beam on the target. An HEL system must also be engineered to be operational in the field. Finally, the overall utility of an HEL system depends on the environment in which it is placed (surface, air, or space) and on the missions it is tasked to perform. This section considers the component and system level challenges of an HEL weapon system.

Laser Devices. The aforementioned classes of HEL currently under development are chemical lasers, solid-state lasers, and free-electron lasers. Work on other types of HELs, such as the gas dynamic laser and the pulsed electric gas discharge laser, was discontinued years ago because the lasers produced beams at unfavorable wavelengths for propagation. Technology issues (as developed in the DOD HEL Science and Technology Investment Strategy of November 2001) are different for each type of HEL but include scalability, beam quality (ability to focus beam), and laser line (wavelength) selection for optimum beam propagation. Issues peculiar to each type of laser include laser reactant and effluent handling (chemical lasers); thermal management and low-cost laser diodes (solid-state lasers); and high-current photo-injectors, high-damage threshold resonator optics, and high-efficiency wigglers (free-electron lasers).

Chemical lasers are the only class of HEL currently able to achieve megawatt power levels. The MIRACL is a deuterium fluoride (DF) laser operating at a wavelength of 3.8 microns that has been in continuous operation at the megawatt level since the mid 1980s at the White Sands HEL Systems Test Facility. It was originally conceived as a test bed for ship self-defense but suffered from propagation losses at full power. The Navy discontinued development of chemical lasers because of the inherent propagation losses in the operational wavelengths. However, DF technology found a home in the U.S. Army/Israeli THEL, where propagation losses are mitigated by lower power levels and a crossing target. The THEL demonstrated its capability against Russian 122-millimeter (Katyusha) rockets in a multimissile engagement in late 2000. The THEL, however, is not a mobile system and was designed specifically for Israeli border defense. Concepts for a mobile THEL (MTHEL) are currently under consideration. Questions remain as to how well the THEL would operate in a battlefield with smoke and dust.

The hydrogen fluoride (HF) laser is similar to the DF laser but operates at a shorter wavelength (2.7 microns), which will not propagate well in the atmosphere but will perform well in space, potentially for ballistic missile defense. The Missile Defense Agency has recently cut back the space-based laser program, and no date can be set for potential deployment.

More near term is the Air Force/Missile Defense Agency ABL for theater missile defense. The ABL employs a COIL that operates at a still shorter wavelength of 1.3 microns. The shorter wavelength allows the focusing of the beam to the required spot size with smaller optics than with longer wavelengths. Chemical lasers have acceptable beam quality (ability to focus the beam) that can be improved with adaptive optics. Reactants for the COIL include hydrogen peroxide, chlorine, and iodine; the HF and DF lasers use gasses containing hydrogen, deuterium, and fluorine, requiring special handling and disposal of the effluents. These lasers require pressure recovery (ejectors) from the low-pressure laser cavity unless operated at high altitude or in space. Due to the gas handling, the laser cavity, the large optics, and the ground-based pressure recovery, these devices are relatively large. The ABL system, for example, will fill a Boeing 747–400 series freighter aircraft.

Free-electron lasers could be designed to operate at any desired frequency and are, to a degree, tunable in operation. At ground level, they might have the best chance of producing a beam that propagates successfully through the relatively dense or "thick" air. Since the laser beam is produced in a vacuum cavity, the beam quality is excellent. Significant technical challenges exist both to scale the beam to megawatt powers and to engineer a laboratory device into a weapon system. The principal scaling issue is in generating an electron beam (high-current photo-injectors) with about a three-orders-of-magnitude increase of current over the existing kilowatt-class laser. Another risk technology area is with the resonator optics needed to extract the light from the resonator electron beam in a practical length. The FEL is the most complex of the three HEL alternatives and most likely is suited only for ground or shipboard use.

Solid-state lasers have the most potential for a compact engineered weapon, although current devices are still large and complex. The laser does not require flowing exotic gases or relativistic electron beams. The system could be inherently smaller and less complex than the other laser concepts. The lasers also operate at about 1.06 microns, lower wavelengths than the COIL, which further simplifies the optics. However, solid-state lasers have the largest challenge to scale up to megawatt power levels because of waste heat removal. Waste heat from a chemical laser is carried off in the flowing gas medium. The unexpended energy in the electron beam of a free-electron laser can be disposed of in a large heat sink. But with a solid-state laser, the waste heat remains in the laser medium, increasing the temperature in the medium until lasing with acceptable beam quality is impossible. Several techniques to combat this problem are being studied. The current options are short pulses followed by cool-down, cooled geometries, including fiber-optic laser bundles, and slab lasers. Increasing laser efficiency will also reduce the amount of waste heat. Combining the power output of many smaller lasers into a single high-power coherent beam has also been investigated. With this concept, some of the system simplicity advantages would be lost. However, the fiber-optic laser successfully uses the principle of beam combination.

A final important technology area for solid-state lasers is the development of affordable, high-power laser diodes to pump the laser to the excited state necessary for lasing. For example, a half-megawatt laser that is 20 percent efficient using 10-watt diodes will require 250,000 pump diodes. With diodes costing more than $100 each, the price of the diodes alone would be more than $25 million.

At minimum, costs must be reduced by an order of magnitude. While there is a large industrial market for laser diodes for commercial application, there is as yet no other market for the high-power diodes needed for an HEL.

Optics and beam control. Significant progress in this technology area has led to optical pointing and tracking accuracies, which can hold a laser beam on a given target at current ranges of interest for the required kill time. In fact, technology transfer from HEL adaptive optics development has contributed to the current generation of ground-based telescopes for astronomy. Principal future gains to be made are in large lightweight deployable optics, particularly for space; advanced adaptive optics to remove beam aberrations both in the laser cavity and in transmission through the atmosphere; and windows, coatings, and deformable mirrors to handle high-power beams and improve the ability to correct for stressing atmospheric aberrations in the propagation of the beam. Techniques for the pointing and tracking of a laser beam from a moving platform to a moving target through a fluctuating atmospheric medium need to be developed and tested for precision engagements at extended ranges. Real-time characterization tools for the atmosphere must also be developed for HEL deployment. Utilizing the beam director as an imaging telescope, algorithms need to be developed to process the imagery for target identification and rules of engagement.

Propagation through the atmosphere. Propagation of a high-energy beam at ground or sea level, where the air is relatively dense, has been the single most limiting factor in the Navy's ability to field a shipborne HEL cruise missile defense system. In space, this problem does not exist and is significantly less for the ABL at altitude. The principal loss mechanism the Navy has experienced is a nonlinear process called *thermal blooming,* in which absorbed energy in the air creates a negative lens that defocuses the beam. Increasing the power of the beam increases the energy absorbed and worsens the problem. Thermal blooming is nonlinear; it evolves over a horizontal path that has atmosphere all the way to the target. Therefore, closed loop adaptive optics techniques have not proven effective. To address this problem, the Navy is developing free-electron lasers that can generate wavelengths at which absorption and thermal blooming are minimized.

Turbulence-induced defocusing causes another loss mechanism that is more severe at shorter wavelengths. This loss mechanism, however, has been amenable to partial cleanup by adaptive optics employed on the ABL. A major issue for the utility of lasers, particularly at ground and sea level, is that of propagation in weather and battlefield dust. Aerosols significantly reduce propagation both by the mechanisms of absorption and by scattering. Lasers operate in the near infrared rather than the visible frequencies, but the laser generally will not propagate well in any environment of limited visibility (such as in heavy fog). A requirement for all-weather lethality could limit the utility of an HEL as a stand-alone weapon. This drawback is only partially relieved by the fact that missile seekers, including millimeter wave radar seekers, are also degraded by weather.

substantial advances during the past 30 years of HEL development have resulted in fieldable laser systems such as the ABL

Lethality. Several variables affect lethality from an HEL, namely the spot size on the target, the energy transmitted to the target, the coupling of the energy into the target (as a function of both the beam characteristics and the target characteristics as changed over time by the damage), and the disruption and destruction of the target due to the damage imposed by the beam. Chemical lasers produce a continuous rather than a pulsed beam. The damage mechanism to a target is due to thermal heating of the surface causing melting and ablation. The lethality mechanism for the ABL and the THEL is ignition of the rocket or booster propellant by irradiating the thin case of the booster. The uncontrolled solid propellant burning out of the side of the motor destroys the missile. For a liquid propellant under pressure, the stress-induced crack propagation could lead to total failure. Other lethality mechanisms include a guidance and control kill, a warhead kill (the warhead is usually less vulnerable than the propellant), or an aerodynamic kill, in which the missile is damaged to the point that aerodynamic forces tear it apart. Solid-state lasers operate in a pulsed mode, in which additional damage mechanisms may augment a pure thermal kill. Very high pulse energies can create shock and spallation in a target, and interpulse intervals could allow time for laser debris to clear out of the path of the beam. Free-electron lasers operate at a very high repetition rate effectively similar to that of a continuous beam. Lethality technology needs a predictive and validated modeling capability as well as more studies using various beam pulse widths, pulse rates, and irradiances. In addition, lethality modes other than ignition of warhead or propellant, including guidance and control and aerodynamic kills, need to be investigated for high-speed missiles.

Engineering. High-energy lasers of the megawatt class provide significant challenges in both design and integration into mobile platforms that induce shock and vibration. Substantial advances during the past 30 years of HEL development have resulted in fieldable laser systems such as the ABL. Among the advances are material development, computer aided design, computational fluid mechanics, micro-machining, dynamic vibration control, large lightweight optics, and diamond-turned optics, windows, and coatings. The current generation of HELs is chemical lasers. Despite all of the advances, they are still large, complex, integrated fluid mechanical and optical systems that require highly skilled operators and considerable maintenance. They also involve chemicals that need special handling. Free-electron lasers, currently at the kilowatt level, are even more complex. They operate at electron beam energies requiring shielding, high vacuum, and probably cryogenic cooling. Electron beam control and vibration control are critical for high efficiency operation. Even clever packaging most likely will result in a system larger than the other laser concepts. Solid-state lasers show the most promise for relative simplicity but are also still at the kilowatt level with significant unresolved scale-up issues, both in the laser

design to handle the thermal management and the laser diodes. As the laser kill range increases, the requirements on the optical systems increase. To maintain a spot with centimeter-level stability over 100 kilometers requires submicroradian control.

HELs are at the beginning of their acquisition learning curve and probably will not be manufactured in large enough numbers in the foreseeable future to benefit from the reduced costs associated with the purchase of hundreds or thousands of units. High acquisition, operational, and maintenance costs are to be expected. The main exception to this is the cost of expendables. The cost of the fuel to create a laser beam is negligible compared to the cost of a missile; therefore, the number of rounds fired over the system lifetime is an important parameter. Because of the current uncertainties in performing engineering system tradeoffs, enthusiasm for HELs remains driven by their special or unique attributes.

despite the advantages of space, the operational challenges for an SBL are daunting

Operational Challenges

Space-based lasers. The SBL mission is boost phase in the upper atmosphere and midcourse ballistic missile defense. Operationally, an SBL system would be deployed in a low Earth constellation to provide continuous coverage. The number of lasers in a constellation might be 20 to 35, depending on orbit, laser power, and coverage. There are distinct advantages to operating a laser in space. The vacuum of space allows beam propagation with no losses (the principal shortcoming at sea level). A chemical laser, such as the proposed hydrogen fluoride laser, needs to exhaust the laser cavity at low pressures. The vacuum of space solves the pressure recovery issue. Finally, freedom from gravitational forces allows for some relief from structural considerations. Despite the advantages of space, the operational challenges for an SBL are daunting. They include lift to orbit and space assembly, stable and reliable operation in space, and maintenance and resupply of fuels. The problems and cost associated with the deployment of a constellation of megawatt-class chemical lasers with multimeter diameter optics are challenging. The SBL program is still in the stage of developing a plan for a subscale integrated flight experiment; a full deployment plan has not been developed.

A number of HEL operational issues are more difficult in space than on the ground. For example, the chemical laser has many of the attributes of a rocket motor, to include thrust and combustion instability driven vibration. On the ground or even in the ABL, this issue is handled by massive supports and by isolation of the laser flow system from the optical system. In space, thrust from the exhaust must be carefully balanced to hold the laser system in orbit and to allow the optical system to maintain track on its target. Dynamic vibration control must also be employed to keep beam jitter to the very low levels required from the beam director. Another potential issue is the dispersion of the laser exhaust. If the laser beam were to pass through the exhaust, it could be significantly attenuated and distorted. The exhaust, which is corrosive, could also damage the optical system. Due to the need for vacuum and zero gravity for a realistic test, eventually, the potential impact of these concerns will have to be tested in space.

Airborne lasers. Currently, two airborne operational missions utilizing a laser weapon are under development: the ABL for boost-phase missile defense and the ATL (a new program just under way) for air-to-ground operations. The ABL, the HEL system closest to operational test, is arguably the largest and most complex piece of military hardware ever flown in an airplane, as well as being the most expensive. Nonetheless, the operational issues of the ABL appear to be tractable and are considerably less than those of the SBL. The platform is much larger, the system is manned, and maintenance and refueling are done on the ground. Due to the complexity of these HEL systems, field maintenance would require specialized equipment and highly trained maintenance crews, possibly even dedicated support shelters. System readiness is paramount if the primary mission of the HEL is missile defense. From an operational point of view, the ABL system bears similarities to the airborne warning and control system (AWACS). Both are large systems required to be on station continuously at a high state of readiness. For boost phase missile defense, it will be necessary to forward-deploy the ABL. The Air Force plans to be able to deploy and be on station within 24 hours of initial threat warning and to maintain two ABL aircraft in orbit continuously at 40,000 feet.

Another concept for an airborne laser is the ATL for surgical strike or nonlethal operations, particularly in an urban environment. While one would not consider using a megawatt-class weapon as an antipersonnel weapon, devices of significantly lower power are still classed as an HEL and form the basis of the ATL concept. The ATL will investigate the use for a laser with power from the tens to a few hundreds of kilowatts to disable ground targets such as wheeled vehicles from an air platform such as a helicopter. The current plan to investigate military utility and operations for the ATL is to build a fieldable prototype and experiment with operational utility.

Ground-based lasers. The THEL system, designed for air defense against rocket attack, is a fixed, nonmobile system. Operational considerations for this system, which has shown considerable success in testing, would require the system to be mobile or at least easily transportable unless used to defend a fixed site. The September 11, 2001, attacks on the United States have raised the issue of systems to support homeland defense. Just as lasers have been evaluated for the defense of high-value ships at sea, the HEL could be a strong candidate for defense of high-value facilities in the homeland. A potential first application of a free-electron laser could be to defend a nuclear power facility in which the real estate and prime power for the laser are readily available. The advantage of an HEL for homeland defense is that the laser does not provide a threat to the area it is protecting. This may not be true for missile air defense systems currently being installed. Projectiles used for homeland defense need to be self-destructing before they reach and potentially damage ground infrastructure. As it stands now, a launched air defense missile could provide a hazard to residents and homes if it failed to engage a target. Of course, a target brought down by an HEL

also would constitute a threat to the ground. Similarly, the placement of explosive missile warheads and missile propellants near a power facility or other high-value facility creates its own peril. An electric powered laser would have no reactive materials, and the beam would not provide a hazard to the ground. A nearer-term HEL system for homeland defense could be a derivative of the chemical laser THEL.

Although external target acquisition is still required, an HEL beam director system serves as its own precision pointing and tracking system, providing azimuth, elevation, and range information. The system also can provide imagery for target identification. In engagements in which threats must be discriminated from friendly and commercial aircraft, or in urban environments, the fire control system must be programmed to shoot only at threats. Such rules of engagement are already programmed into the THEL system whereby it is specifically programmed to shoot only at Katyusha rockets. In general, allowance must be made to accommodate different rules of engagement rapidly and to allow for human intervention where time permits.

Ship-based systems. From an operational point of view, a Navy ship might seem an ideal platform for an HEL. Ships are far larger than other platforms, and ship defense against cruise missiles is a clearly defined mission. The current lack of a Navy HEL development program is due to the technical issues of propagation and lethality rather than to operational issues. At this stage, an HEL would have to show advanced performance at an affordable cost through a tradeoff study of alternative systems and missions. Pop-up threats such as small speedboats and jet ski watercraft, as well as cruise missile defense, are valid missions. If an HEL system is compared to an alternative system such as a missile or hypervelocity gun system, the entire system must be considered on a mission-by-mission basis, including threat characterization, raid size, and weather. The system elements are target acquisition, target tracking, command and control, and the weapon system (or weapon systems in a layered defense). A weapon system may also be an integrated HEL and missile system.

Policy Issues

Space-based lasers. While the withdrawal from the Anti-Ballistic Missile Treaty has expanded the envelope for HEL employment, significant policy issues (in addition to technical and operational issues) remain for space-based lasers. To field an SBL is to put a weapon system in space that other countries (particularly Russia and China) would consider as escalating the U.S. strategic capability. While the concept of the SBL is for defense against intercontinental ballistic missiles (ICBMs) in boost and mid-phase, the SBL also would have the capability to destroy or disable other space-based systems such as surveillance satellites. Although the HF chemical laser technology currently being planned would not produce a beam capable of propagating through the atmosphere, future laser concepts could put airborne or even ground targets at risk. By definition, a space-based defensive weapon is always armed, always overhead, and in constant flight over other countries. This is true not only for potential enemies but also for our allies and the U.S. homeland. To be effective, an SBL would require a high level of autonomy so that it could react promptly to pop-up threats and reduce the risk of jammed or subverted data links. This capability would require levels of reliability well beyond that of laser systems with manned operators, as well as periodic and frequent maintenance. The system would also need to be survivable against a wide assortment of countermeasures that a country with space capability could employ. Finally, the cost of a constellation of SBLs to achieve continuous coverage will be extreme (no reliable figures are available, but they might approach $100 billion). This cost would need to be weighed against funding other elements of the missile defense system as well as other DOD priorities.

to field an SBL is to put a weapon system in space that other countries (particularly Russia and China) would consider as escalating the U.S. strategic capability

Airborne lasers. The range of the ABL system (on the order of 200 miles) and its mission of boost phase intercept against Scud missiles, rather than ICBMs, would greatly limit its utility against Russia or China, where missile silos are at considerably greater distances than 200 miles from their borders. An ABL would not have continuous presence, its defense would be limited to specific threat areas, and it would be a manned system. Therefore, the ABL should not be perceived as a realistic threat to the strategic assets of other countries. However, the survivability and implications of an attack on an ABL are of some concern. If an HEL is used for ballistic missile defense, an attack on that system becomes an attack on a strategic asset that could presage a missile attack. Defensive considerations for an ABL could include self-defense by either the HEL weapon system itself or an auxiliary weapon system used for escort support or deployment beyond the range of ground-based air defense. The defensive situation for the ABL is similar to that of the AWACS surveillance aircraft, which relies on standoff and escort as its principal tactics for survivability. Both policy and operational considerations dictate the deployment of a strategic asset. From a policy point of view, keeping an ABL out of harm's way is advisable, since an attack on it would tend to escalate a confrontation from tactical to strategic. On the other hand, from an operational point of view, it is necessary to get an ABL within lethal range of the boost-phase flight path of incoming missiles. Accordingly, deployment of an ABL against Russian or Chinese strategic missiles, with its currently projected range, might be possible operationally but problematic in policy.

The ATL is designed to disable ground targets in an urban environment. An overarching policy concern for this concept is that U.S. policy does not permit the development of weapons primarily designed to create permanent eye damage or blindness. While this is not the objective of the ATL, the potential exists that reflected or scattered light from an ATL could cause eye damage if the laser were

used near people. Retinal eye damage can occur at low levels of intensity (tens of milliwatts) at wavelengths that pass through the cornea. The cornea itself can be damaged by absorbed light at watt levels of energy. Occupational health studies have set the wavelength at which light does not pass through the cornea at 1.5 microns and above. DF and HF chemical lasers, CO^2 lasers, and FELs operate above 1.5 microns, while COIL (at 1.3 microns) and solid-state lasers (generally at 1.06 microns) could cause concern for low-power-level retinal damage. While these concerns exist, the inherent precision of a laser and the ability to tailor the energy required for effect to specific target vulnerabilities should greatly reduce the potential for collateral damage.

the ABL is the system closest to deployment, with difficult but tractable technical and operational challenges and a clear mission

Ground- and sea-based lasers. Over the years, the Army has looked at a number of ground-based HEL concepts, including missile defense and countersensor lasers. The principal development from the Army is a system jointly developed with Israel for defense against Katyusha rockets. While there are no policy concerns with the THEL as an air defense system, a more general issue is how this technology could create policy issues involving the export of laser technology to other countries. For example, a ground-based system scaled to higher powers than the THEL could be used to disable satellites. At lower powers, a laser beam at wide aperture slewed rapidly could be used as a nonlethal weapon for crowd control (much like a long-range fire hose). The use of a millimeter wavelength beam is also being examined for nonlethal applications. The Navy has looked at reducing the power of an HEL to use at sea as a warning device to approaching small craft. At higher laser powers, the craft, such as a speedboat or a jet ski watercraft, could be damaged or destroyed (a difficult task for a 5-inch gun). Of these potential uses, all raise the issue of employing antipersonnel weapons that may cause blindness.

Conclusions

Currently, the HEL is a niche weapon only operationally competitive against other weapon systems where speed-of-light engagement is essential for defense of high-value assets, particularly against ballistic missiles with weapons of mass destruction. The ABL is the system closest to deployment, with difficult but tractable technical and operational challenges and a clear mission of boost-phase missile defense against potential rogue state threats. If the range of the ABL were to be significantly increased, perhaps to 700 miles, the system also could be considered a threat to the strategic assets of major powers, thereby creating diplomatic issues. Other missions for HEL still require technology and engineering advances along with convincing demonstrations that they can compete against more conventional missile and gun weapon systems. Ground-based lasers have been effective against rockets in the THEL demonstrations, but a mobile system has not yet been engineered. Similarly, space-based lasers are nowhere near deployment. Significant technological, operational, and financial issues need resolution. There is the added possibility that a space-based system could attack not only ballistic missiles but also any other air or space target. A different laser concept than the HF chemical laser, whose beam could propagate to the ground, could attack ground targets. Introducing such a weapon system is a major policy decision with global and national ramifications. On a smaller scale, while the Navy has a clear mission for ship defense against cruise missiles, technology issues still preclude a viable sea-based system. A laser such as the free-electron laser, capable of producing a beam that will propagate through the maritime atmosphere, needs further development to make this concept viable. DOD is continuing to experiment with an airborne tactical laser to address ground targets such as light vehicles. The antipersonnel aspects of such a system will provide operational and policy challenges. The potential for a fixed-site HEL system to defend high-value facilities such as nuclear power plants also warrants continued investigation. Advances in laser devices (particularly in solid-state lasers), in optical components, and in beam control would greatly expand the potential mission viability of HELs.

After 30 years of development, the revolutionary concept of the high-energy laser is now proceeding through evolutionary advances. While no fundamentally new laser concepts have emerged in the past few years, significant progress has been made in scaling lasers to higher powers, in creating adaptive optics, and in engineering the laser system for applications. As the power and compactness of the HEL improve, the potential missions and applications will increase. A continued, measured investment in HEL research and development is certainly warranted.

Defense Horizons *is published by the Center for Technology and National Security Policy through the Publication Directorate of the Institute for National Strategic Studies, National Defense University.* **Defense Horizons** *and other National Defense University publications are available online at http://www.ndu.edu/inss/press/nduphp.html.*

The opinions, conclusions, and recommendations expressed or implied within are those of the contributors and do not necessarily reflect the views of the Department of Defense or any other department or agency of the Federal Government.

Center for Technology and National Security Policy

Hans Binnendijk
Director